# Making Oxygen on Mars

*The Mars Atmosphere Resource Recovery System*


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## Background

The Mars Atmosphere Resource Recovery System (MARRS) is a thermophysical process that extracts oxygen, water and other valuable constituents directly from the martian atmosphere. Oxygen makes up over 0.1% of the surface atmosphere. The MARRS process efficiently removes this and other valuable constituents including water, and can produce substantial amounts of electrical power as a bonus.

Under a Phase I NIAC grant, the first conceptual design of a plant to recover minor atmospheric components on the surface of Mars was conducted. The design showed that the direct extraction of oxygen and water from the martian atmosphere is technically feasible, and, when implemented on a scale suitable for human exploration, uses less energy and requires less launch mass than other proposed resource recovery methods.

For robotic outposts on Mars, direct extraction of resources from the atmosphere can produce propellants for surface use or Earth-return. The design of the plant will differ from that of a human exploration mission, being smaller and less able to benefit from economies of scale. Direct extraction might be combined with other resource recovery methods to provide a balance of products such as both fuels and liquid oxygen for optimum sample return to Earth. Redundancy associated with piloted activities, of course, might be eliminated.

Figure 1 outlines how the naturally occurring oxygen and water are recovered. The thin atmospheric gases are compressed, and the dominant component, carbon dioxide ($CO_2$) is condensed. This simple step concentrates the remaining gases by up to 25-fold, making them easily recoverable by conventional purification methods such as air distillation. Further compression recovers water as ice, and subsequent cooling and cryogenic separation produces pure liquid oxygen and liquid carbon monoxide (CO), the latter an important natural constituent of the martian air.

The liquefied $CO_2$, available in large quantities, is expanded back into the thin atmosphere to recover most of the energy needed for compression. The raw energy to drive the extraction process is supplied as heat, most likely from a nuclear or radioisotope source. Some liquid $CO_2$ can be stored for use in backup power systems and any other operation that can make use of an expanding working fluid. This feature makes the MARRS process a highly flexible basis for a martian surface architecture for large robotic and human exploration missions. Liquid $CO_2$ is the "steam power" for Mars.

The key questions as to the feasibility of the MARRS direct extraction process include (1) its benefits over currently proposed oxygen production methods, and (2) the mass and energy requirements for a substantial mission to Mars. To aid in addressing these questions, the Mars Reference Mission (MRM), under continuous study at the NASA-Johnson Spaceflight Center, was used as the yardstick from which the needed estimates were made.

Major Findings for NIAC

1. Oxygen requirements for the MRM can be met with a MARRS plant driven by a 120 kilowatt thermal heat source. This plant produces twice the liquid oxygen needed for Earth return and twice the oxygen needed for crew respiration. The plant produces 5.8 kg/hr of liquid oxygen at 16% efficiency. Evolved technology would produce correspondingly more products as efficiency increases.

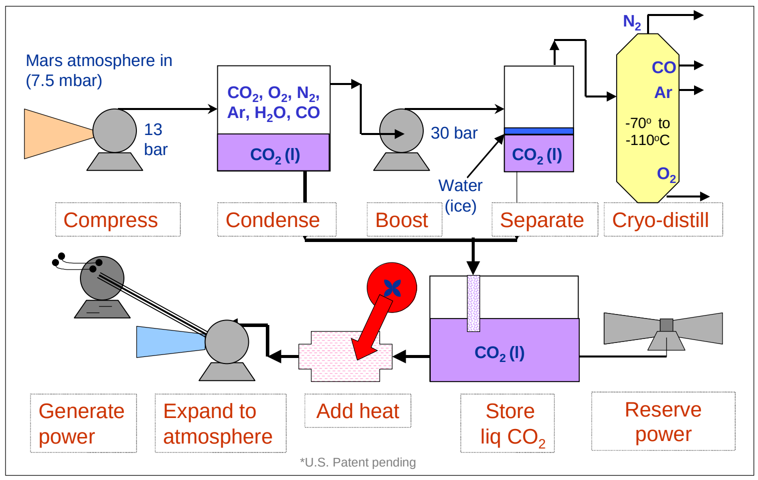


Fig. 1. Elements for Atmospheric Resource Recovery

2. MARRS can recover up to 1 kg/hr of pure water while producing oxygen for the MRM. The production rate, however, will be highly variable according to season, latitude and location. Landing sites could be selected based on water recovery prospects.

3. MARRS can produce the oxygen needed for the Mars Reference Mission (MRM) with less mass and less energy than electrolysis-based methods. These benefits accrue from several factors including (a) efficient use of the cold martian environment to reduce energy requirements, (b) economies of scale obtainable in continuous materials-handling processes for fluids, (c) recovery of multiple useful products including water and carbon monoxide with virtually no added equipment, (d) the use of heat as the primary energy source, and (e) the integral production of electrical power within the MARRS process.

4. The main technical uncertainty of the MARRS process is the technology to compress the thin dusty Martian atmospheric gases efficiently and reliably to the needed processing conditions. The optimum technology will depend strongly on the size of the plant. Small plants may benefit from simple thermal-swing compression technology currently being studied by NASA. At the largest sizes, axial compression, familiar to jet engines, is the method of choice.

5. The production rate for oxygen may be substantially higher than estimated, or, correspondingly, the energy and mass lower. While the conceptual design assumes an atmosphere containing 0.13% oxygen, studies show that this value may be substantially higher (up to 0.4%). As a result, oxygen production as well as energy and mass estimates in this report are likely highly conservative.

When examined in the context of the NASA-JSC Mars Reference Mission, MARRS could save over 15,000 kg of launch mass, possibly as much as 30,000 kg. The reduction is derived primarily from (a) the simplicity and low energy requirements of the process attributable to the efficient utilization of the martian environmental conditions, (b) the large production rates of products that reduce the transportation requirements for consumables, (c) the availability of a fuel precursor (carbon monoxide) in substantial quantities, and (d) offsets for mass needed in the MRM for air revitalization and air conservation on Mars. More studies are required to assess these benefits.

A Martian Surface Architecture

A direct extraction process provides the opportunity to recover oxygen, water and other products using only heat as an energy source and without the need for either high temperature operations or chemical reactions. The conventional chemical engineering design for a thermophysical process allows for a confident design based on established design principles.

Figure 2 shows how an atmospheric extraction pro-cess can be the basis of an entire surface architecture . Using heat and generating power by expansion of the extracted gases, MARRS can be configured into a highly redundant resource recovery system that includes massive amounts of power storage as liquid $CO_2$.

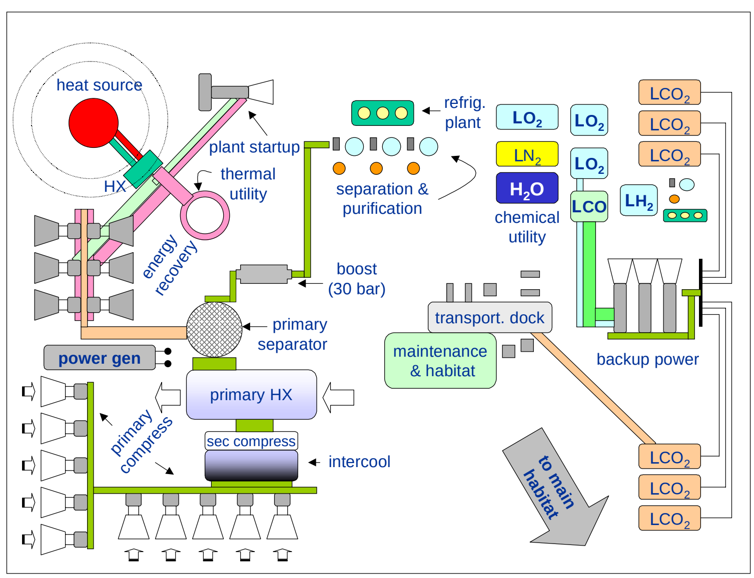


Fig. 2. A Mars Outpost Architecture by Atmospheric Resource Recovery

The MARRS process uses the cold martian environment to very great advantage. Its qualification as the basis of a surface architecture comes largely from taking advantage of the cold martian temperatures. Removal of the $CO_2$ from the oxygen and water is highly efficient at these temperatures. MARRS also makes efficient use of a heat source that can be made highly robust. Temperatures are compatible with the use of stainless steel rather than more refractory alloys. Other in-situ processes fail to take advantage of the engineering advantages of the low temperature environment.

Technologies for the production of oxygen and water on Mars are enabling for human habitation, and for return of martian samples in quantity. These resources are needed to manufacture propellants for return-to-Earth voyages, and, of course, for sustaining human habitation for extended periods.

Of high importance is be a technology that produces all the components of breathable air, and in substantial quantities. The amount of recycling of waste products can be reduced so that revitalization equipment may be correspondingly reduced. Mission improvements associated with the reduced need for resource conservation also reduce mass as are hazards associated with biological contamination within crew quarters.

### Production Rates for Oxygen, Water and Other Products

After energy recovery, the overall efficiency of MARRS is estimated as 16% using a nuclear heat source. For a 120 $kW_{th}$ heat source, the production rates are 5.8 kg/hr of oxygen, 0.6 kg/hr of water, and 2.9 kg/hr of carbon monoxide (corresponding to ~0.24 kg/hr of hydrogen, or ~2 kg/hr of methane). Corresponding values for the potential electric propulsion propellants of neon, krypton and xenon are roughly 12, 6 and 3 grams per hour.

### Martian Environmental Variability

A major finding of this study is that the Martian surface environment is very poorly understood from an engineering point of view. Only scattered surface measurements have been made of temperature, pressure and composition (the thermodynamic variables). Diurnal variations in density, sometimes as much as 30%, will dramatically affect the design of any process that utilizes the surface atmosphere. For example, an energy-poor mission might operate a compression plant only at night when the atmospheric density is relatively high.

Seasonal and multiyear variations in pressure and composition will influence design as well. Up to 30% of the atmosphere is removed at the South Pole each year, likely raising the global fraction oxygen and carbon monoxide. This increase would change compression energy and equipment requirements by a like amount.

### The Accuracy of Martian Surface Composition Information

The surface composition of the atmosphere, shown in Table 1, is the generally accepted one. Examination of the sources for this information indicates that the values are only approximate. The surface concentration of carbon monoxide, for example, has not yet been measured. Its value reflects satellite observations that include the entire atmospheric column. Atmospheric models, however, show that the production rate of carbon monoxide and oxygen, produced by photolysis of carbon dioxide, are highest at the surface.

Table 1 also shows our estimate of the range of possible concentrations at a north latitude site such as the Viking 2 lander site. Oxygen may be present at concentrations of up to 0.4% by volume. If so, estimates for oxygen production rates from MARRS might be tripled, or energy reduced by 65%.

| Component | Nominal | Range |
|---|---|---|
| | | |
| $CO_2$ | 95.32 v% | 94-97 |
| Nitrogen | 2.7 v% | 2-3.5 |
| Argon | 1.6 v% | 1-2.5 |
| Oxygen | 0.13 v% | 0.1-0.4 |
| CO | 0.07 v% | 0.02-0.14 |
| Water | 0.03 v% | 0.005-0.04 |
| Neon | 250 ppm | 100-400 |
| Krypton | 30 ppm | 15-50 |
| Xenon | 8 ppm | 3-20 |
| Ozone | 3 ppm | 0.5-20 |

Table ES-1. Composition of the Martian Surface

Satellite data show a wide variability in column abundance of water, both regionally and seasonally. It is expected that surface concentrations will be greatest in the Northern Hemisphere, especially during northern spring and summer. The atmospheric concentration of water may drive the selection of a site for a MARRS plant.

Process Elements of MARRS

Figure 3 illustrates the major elements of direct extraction to recover oxygen. The major inputs are thermal energy and martian atmospheric gases, and the products include oxygen, carbon monoxide and nitrogen. Water is recovered as ice within the process as described later.

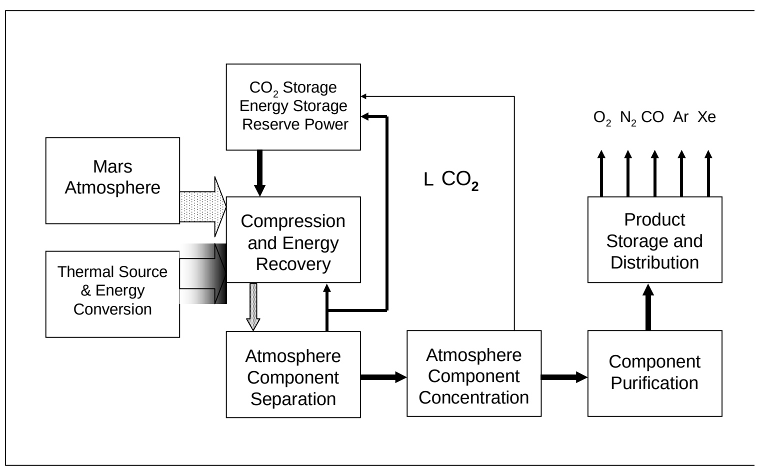


Figure 3. Major Elements of the MARRS Direct Atmospheric Extraction Process

Dust-tolerant robust compressors provide a high-density dust-free gas to higher-performance compres-sors that raise the gases to pressures greater than 1300 kPa (13 bar). Intercooling recovers much of the compression heat and lowers the total compression power. Cooling then liquefies the major component, $CO_2$, leaving behind oxygen and other valuable gases. Still more compression supplies a product-rich gas for purification and storage. Most of the compression energy is recovered by expansion of the compressed and liquefied $CO_2$ back into the low-pressure martian environment.

Why Direct Extraction Works on Mars

A key feature of the martian atmosphere is that the majority component, $CO_2$, is near its condensation temperature, thus enabling its removal with a low energy expenditure. Figure 4 illustrates the effects of removing $CO_2$ on the concentration of the remaining components. The top bar shows the amounts of components in the atmosphere under "normal" conditions with oxygen at 0.13%. The middle bar shows the amounts of components remaining if a closed container were cooled to a temperature typical of the martian poles. Oxygen is concentrated over ten-fold to 1.5%. The bottom bar illustrates that even higher concentrations of oxygen can be produced by compression, and, in addition, $CO_2$ occurs as a conveniently handled liquid. The MARRS process follows the compression approach in the bottom bar that can produce a gas rich in oxygen, carbon monoxide and water.

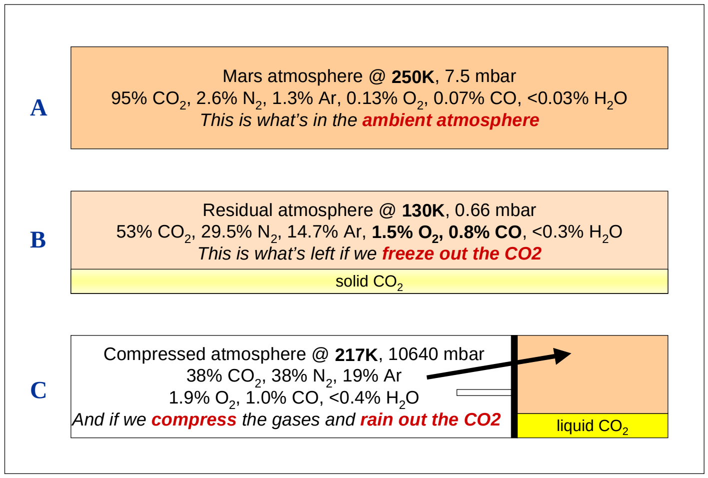


Figure 4. Illustration of Gas Composition Changes Resulting from $CO_2$ Condensation

A key design principle of MARRS is that the process operates at sufficient pressure to condense carbon dioxide as a liquid. At this pressure, the triple point pressure of $CO_2$, the volume of gas is reduced by a factor of about 12,000 from its volume at martian ambient pressure. The remaining gas can be processed efficiently in conventional equipment that is physically small.

Mars Reference Mission (MRM) Requirements

For human exploration of Mars, oxygen is needed for propellant as liquid and gaseous oxygen, for respiration as a 20% mixture with nitrogen and argon, and for a variety of biological and sanitary uses. By far the largest requirement is for liquid oxygen propellant part of a propulsion system for Mars ascent and Earth return.

Table 2 provides a summary of oxygen requirements that forms the basis for the MARRS design. Single redundancy is assumed for both propellant and respiratory oxygen with the assumption that water electrolysis or other technology will provide additional backup. The MARRS design is sized for recovery of 58600 kg of liquid oxygen.

The MRM suggests the transport of water from Earth with substantial recycling and reclaiming of waste. MARRS recovers water in amounts up to about 100 grams of water per kg of oxygen at favorable locations and times of year where the mixing ratio of water may be as high as 0.03%. At favorable northern latitudes, for example, MARRS can recover as much as about 2,900 kg of water, assuming recovery for half of the martian year.

| CREW OXYGEN | | LIQUID OXYGEN | | TOTAL | |
|---|---|---|---|---|---|
| Respir-ation | Redundancy | Propellant | Redundancy | | per 550 sols |
| kg/hr | kg/hr | kg/hr | kg/hr | kg/hr | kg |
| | | | | | |
| 0.33 | 0.33 | 2.57 | 2.57 | 5.80 | 58600.00 |
| | | | | | |
| Assumptions: 550 days production, 75% availability | | | | | |
| 1 kg $O_2$/sol crew, MRM reqmts 26000 kg LO2 propellant | | | | | |

Table 2. Oxygen Requirements for MRM Mission

Water recovery by MARRS is a direct savings of Earth-transported material, and provides a substantial reduction in Earth launch mass for the MRM. An estimate of the improvement can be made if the landed mass is assumed to be about 10% of the Earth launch mass, or a savings of 29,000 kg launch mass.

MRM does not provide a requirement for carbon monoxide. MARRS, however, provides it at nearly just the cost of storing it. When reacted with water, CO can produce hydrogen or methane, the latter up to 3,900 kg at 100% efficiency. The MRM can greatly benefit from the large production of nitrogen and argon for mixture with oxygen as a respiratory gas. Their availability lessens the need for precision air locks and air revitalization while on the surface of Mars.

## Compression Strategy

A central assumption for MARRS is that $CO_2$ and most products occur within the process as fluids. This approach allows efficient processing with low-mass equipment that can take full advantage of economies of scale. The thermodynamic properties of $CO_2$ require that its partial pressure be raised to above its triple point, or 518 kPa (5.18 bar), to condense as a liquid. Depending on the ambient surface pressure, the needed compression will be from about 500 to 2000 fold.

Multistage compression with intercooling raises the pressure to about 1300 kPa (13 bar). Initial compression to the lowest pressure that is compatible with liquefaction of the majority of the $CO_2$ is assumed the most efficient option for MARRS since it minimizes the amount of gas handled. The product-rich vapors, still containing mostly $CO_2$, are further compressed to above 3000 kPa (30 bar) to condense additional $CO_2$. Water vapor condenses as ice, which floats on the carbonic liquid and is removed mechanically. The optimum pressure for the secondary condensation must be determined by a detailed tradeoff study, not part of the current work. Additional stages that increase pressure to 10 MPa (100 bar) may be desirable to minimize issues associated with removal of $CO_2$ frosts.

A unique part of the design approach for MARRS is to utilize a low ratio “fore-compression” stage to prepare the gases for a conventional multistage compression. Fore-compression removes martian dust, and delivers the gases to subsequent compression stages at constant conditions. This approach is followed to enable optimization of a majority of compression equipment that must operate in an otherwise highly variable environment. Diurnal variation in density, for example, may be over 30% due to temperature changes, and seasonal variation may be over 25% due to condensation at the Martian poles.

## Heat Source Strategy

Heat can be used to great advantage on the Martian surface where the ambient temperature can drop to below –100°C. In this environment, moderate-temperature heat sources such as geothermal and conventional nuclear energy provide as much thermodynamic work as do high temperature (and correspondingly high technology) sources on Earth. Figure 5 illustrates the relationship between heat sink temperature to efficiency. The Carnot efficiency is about the same, for example, with a 400°C heat source on Mars (Label 1) as for a 900°C heat source on Earth (Label 2). There is little theoretical advantage to use high temperature sources.

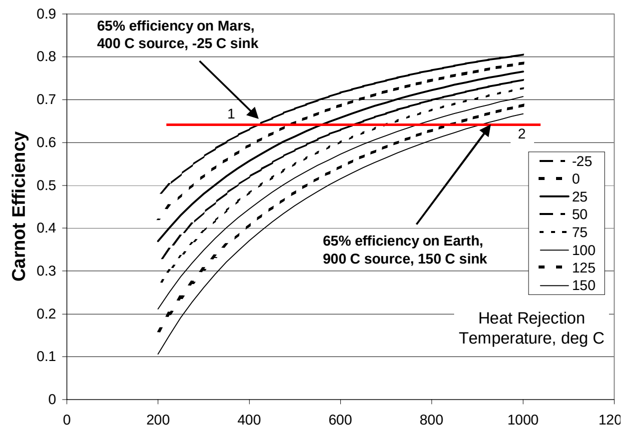


Figure 5. Theoretical Efficiencies for Source and Sink Temperatures

The use of a lower temperature heat source simplifies many practical materials issues. The conceptual design of MARRS assumes a 400°C nuclear source delivering heat at 350°C through a secondary heat transfer loop. These temperatures are compatible with common alloy materials such as stainless steel. The heat transfer fluid, presumed to be argon, is returned at –20°C. A study of nuclear sources or technologies was not conducted as part of the current study.

## Product Recovery Strategies

The initial compression raises the $CO_2$ partial pressure to above its triple point pressure, assuring that, upon condensation, the $CO_2$ will appear as a liquid. Over 95% of the oxygen and similar fractions of the other permanent gases will remain in the gas phase. A simple stripping step using pure nitrogen will remove virtually all the remaining oxygen and carbon monoxide to the gas phase. This product-rich phase still consists primarily of $CO_2$.

The liquefied $CO_2$ ($LCO_2$) is clean and nearly pure, containing only its saturation level of the stripping gas. MARRS stores a substantial amount of $LCO_2$ that is used for energy storage, production control, and as a clean fluid for air bearings. $LCO_2$ is considered a major product of the MARRS process. Additional compression of the product-rich gases to at least 3000 kPa (30 bar) along with cooling to –50°C removes more carbon dioxide. Water will condense as ice on the liquid carbon dioxide if its partial pressure exceeds its vapor pressure. As a solid, water is recovered mechanically from the secondary and higher condensers.

The permanent gases including nitrogen, argon, oxygen, CO, krypton, and neon are recovered from the product rich stream once it is depleted of $CO_2$. Conventional cryogenic separation by distillation recovers highly purified products. This separation is not seen as a technical issue for MARRS. A major process issue is, however, removal of $CO_2$ frosts that will occur as the cryogenic cooling proceeds.

MARRS assumes that $CO_2$ frosts will be removed by the thermal cycling of portions of the separation process. The current study did not evaluate the merits of duplicate equipment to maintain production, but none may be needed. Thermal cycling along with purging to the atmosphere will remove both $CO_2$ and an ozone frost, the latter being an explosion danger that is well known in air separation technology.

## Impact of Variability and Uncertainty on Direct Extraction Processes

The MARRS process was conceived primarily as a method to efficiently extract the 0.13% oxygen from the Mars surface atmosphere by traditional chemical engineering methods. The surface of Mars, however, is characterized by unusually large variations in thermodynamic and transport properties. Wide temperature swings, for example, will affect atmospheric density that in turn will affect heat transfer rates. This variation as well as changes in composition have a first order effect on a direct extraction process, and on any system or process that interacts appreciably with the environment.

The primary uncertainties for MARRS are the amounts of resources that can be recovered. An average oxygen concentration of 0.26%, a good possibility, would cut the mass and energy of oxygen production by half. Diurnal variations in water content may allow highly efficient recovery of water despite its low average concentration. Measurements of composition and of the thermodynamic and transport variables are needed to establish the engineering basis for MARRS and other processes such as heat rejection that interact with the environment.

## Summary of the MARRS Project

Oxygen and the other components of air can be extracted from the martian atmosphere by processes that separate them from the majority component, carbon dioxide, by condensation. The cold environment aids the recovery of these components by reducing the amount of energy required to process the atmospheric gases. The Phase I study for NIAC outlined many fundamentals of the process, and suggested methods that most efficiently extract usable components.

Recommendations for Scientific Study to Support Mars Exploration

1. Determine the extent of the atmospheric resource.
2. Determine the variability of the atmospheric resource.

Recommendations for Engineering Studies to Support Mars Exploration

1. Determine the engineering parameters for convective and radiative heat transfer with the martian environment.
2. Establish methods for design of mass transfer unit operations in reduced gravity.

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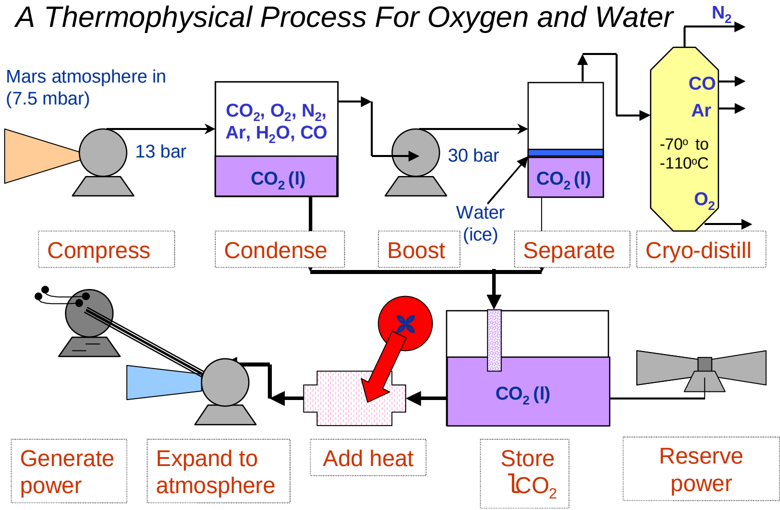
# Making Air on Mars

## The Mars Atmosphere Resource Recovery System

*Enabling Technology for Human Exploration of Mars*

*A Thermophysical Process For Oxygen and Water*




## System/Architecture

- MARRS enables a heat-based surface architecture that makes consumables, propellants, and working fluids in abundance.
- Air is produced from oxygen, nitrogen, argon and water.
- Liquid $CO_2$ is used for reserve and emergency power – a major benefit of a MARRS-like process.
- MARRS produces some water, but other sources may be needed (such as subsurface water-containing substances).
- Reduced scale $O_2$ extraction methods may use alternative approaches for $CO_2$ removal including adsorption.

## Concept/Technology

- Extract molecular oxygen, water and carbon monoxide directly from the martian atmosphere.
- Drop out the majority component, carbon dioxide, by compression and cooling (by HX with the martian environment), then refine the resulting product-rich gases.
- Recover the compression energy by re-expansion to the low-pressure environment.
- Site the plant for the most valuable product – e.g., lowlands for water.
- Use conventional chemical engineering design methods validated for reduced-g.

*Elements of a Surface Architecture*